Flight-Testing of the Self-Repairing Flight Control System Using the F-15 Highly Integrated Digital Electronic Control Flight Research Facility

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FLIGHT-TESTING OF THE SELF-REPAIRING FLIGHT CONTROL SYSTEM USING THE F-15 HIGHLY INTEGRATED DIGITAL ELECTRONIC CONTROL FLIGHT RESEARCH FACILITY

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Abstract

The Self-Repairing Flight Control System (SRFCS) Program is sponsored by the USAF and flight-tested at the NASA Ames Research Center, Dryden Flight Research Facility. The program objective is the proof-of-concept demonstration of the SRFCS using the NASA F-15 Highly Integrated Digital Electronic Control (HIDEC) Flight Research Facility. The program approach exploits the inherent control redundancies of advanced aircraft by fully utilizing its multiple control effectors and optimally integrating their secondary aerodynamic characteristics. This is accomplished by way of reconfiguration after control effector failures. This allows the aerodynamic forces and moments produced by the other control effectors to become the redundant elements instead of massive redundant hardware. The necessary forces and moments are generated by the integration of alternate control surfaces to provide the required aircraft motion. This paper describes the F-15 HIDEC aircraft and the unique features used during the SRFCS flight test program. The development leading to the current SRFCS configuration will be highlighted. The presentation includes preliminary flight test results that address the operation of the overall system, as well as the individual technologies.

The NASA F-15 flight test was the first demonstration of real-time reconfiguration and diagnostics on a high-performance fighter.

Nomenclature

AI	artificial intelligence
CAS	control augmentation system
CND	cannot duplicate
DFCC	digital flight control computer
DFBW	digital fly-by-wire
EGE	effector gain estimator
FDIE	fault detection isolation and estimation
HIDEC	highly integrated digital electronic control
HUD	head-up display
NASA	National Aeronautics and Space Administration
NCI	navigation control indicator
OES	onboard expert system
RTOK	retest OK
SIDC	system impairment detection and classification
SRFCS	self-repairing flight control system
SYSDYN	system dynamic model
USAF	United States Air Force

Symbols

a	amount of span remaining
B^*	impaired control matrix
K	Kalman gain
$\bar{q}$	dynamic pressure, lb/ft^2
$Stab$	stabilator
V_{cas}	velocity, calibrated airspeed, kn
W	weighting matrix
$\ddot{X}_A$	actual aircraft acceleration vector
$\ddot{X}_{Error}$	acceleration error vector
$\ddot{X}_{IMP}$	impaired model acceleration vector
$\ddot{X}_M$	aircraft model acceleration vector
Z^{-1}	one-cycle time delay
α	angle of attack, deg
$\Delta\bar{\delta}$	change command vector

$\Delta \bar{\delta}_i$	incremental change command vector
δ	stabilator actual postion
δ_c	stabilator command
δ_{CAS}	CAS command
δ_{Pilot}	command pilot is giving to aircraft
$\delta_{Surface}$	surface command

Introduction

System failure or aircraft damage causing loss of control capability can compromise mission objectives and even result in loss of aircraft. The self-repairing flight control system (SRFCS) flight development program directly addresses this issue with a system design that can detect flight control system failures or measure damage. The SRFCS can immediately reconfigure the control system command to control the aircraft and even preserve mission potential. Furthermore, the system diagnostics process can detect in flight the type of faults that are difficult to isolate postflight, which can save excessive ground maintenance time and cost. The SRFCS diagnostics feature enhances aircraft alert readiness by reducing ground servicing time.

The control systems of today's fighter aircraft have the control power and surface displacement to maneuver the aircraft in a very large flight envelope, with surplus force capacity available from each control surface. Digital flight control processors are designed to include the built-in status of the control system components, as well as sensor information on aircraft control maneuver commands and response. In the event of failure or loss of a control surface, the SRFCS utilizes this capability to reconfigure control commands to the remaining control surfaces, and thus preserve the maneuvering response. This reconfiguration system permits the damaged aircraft to continue the mission safely or return to base. Damage detection must be fast and accurate, and reconfiguration must restore sufficient flight response.

Correct postflight repair is the key to low maintainability support costs and high aircraft mission readiness. The SRFCS utilizes the large database available with digital flight control systems to diagnose faults. Built-in test and sensor data are used as inputs to an onboard expert system (OES) process to accurately identify failed components for postflight maintenance action. This diagnostic technique has the advantage of functioning during flight. It is especially useful in identifying intermittent faults that are present only during maneuver g loads or high hydraulic flow requirements. These faults are difficult to isolate in current postflight maintenance, resulting in cannot duplicate (CND) inconclusive ground checks and excessive support man-hours.

A number of SRFCS feasibility studies[1-5] have developed and evaluated potential SRFCS method studies. Based on these studies, the USAF Wright Research and Development Center sponsored the SRFCS development and flight test program. The NASA Ames Research Center, Dryden Flight Research Facility worked with the contractor, McDonnell Aircraft Company and subcontractor, General Electric Controls Division. Together they developed the flight system to test the reconfiguration and onboard maintenance diagnostics concepts on the NASA F-15 highly integrated digital electronic control (HIDEC) fighter aircraft.

Key objectives of the program were:

1. To flight-evaluate a control reconfiguration strategy with three types of control surface failure.

2. To evaluate a cockpit display that will inform the pilot of the maneuvering capacity of the damaged aircraft.

3. To flight-evaluate the OES maintenance diagnostics process using representative faults set to occur only under maneuvering conditions.

The objective of the flight test program was to transition real-time reconfiguration and expert maintenance diagnostics technology to the operational community. Flight demonstration is important in validating and evaluating technology for future aircraft. Flight test exposes concepts to the real-world environment, forcing potential problems to be addressed. It also provides indisputable evidence of a concept's validity. In addition, flight evaluation improves the chances of getting a system into production.

Flight Research Aircraft With Self-Repairing Flight Control System

The F-15 HIDEC Flight Research Facility is an ideal candidate for initial evaluation of this technology. A discussion of its unique features follows.

Figure 1 shows the F-15 aircraft flown in the SRFCS flight development program. The aircraft is equipped with a dual-channel digital flight control system and a Hawk/32-bit processor (Rolm Corporation, Santa Clara, California) having a high throughput and memory capacity. Full-authority electronic control of the ailerons was added to the test aircraft through a series servo controller, shown in Fig. 2. Pilot stick commands to the aileron are transmitted by mechanical linkage; the SRFCS reconfiguration commands are added to the aileron through the series servo.

The SRFCS utilized the high-capacity Hawk/32 processor for the major reconfiguration subroutines, the cockpit selection of test modes, the expert system diagnostics, display generation, and flight test data acquisition. Additional flight control computer software included impairment control of the right stabilator, addition of the SRFCS correction commands, and signals used for the expert system diagnostics. A summary of the software requirements to implement SRFCS is shown in Fig. 3.

In addition, the test aircraft required changes to the central computer to link the cockpit navigation control indicator (NCI) control panel and displays to the Hawk/32 processor and the digital flight control computer (DFCC). The pilot

can use the addressing feature of the NCI panel to select the various failure impairments and SRFCS test modes. Figure 4 illustrates the aircraft systems integration for implementing SRFCS.

The NASA F-15 HIDEC contains full instrumentation and data recording with real-time telemetry of key parameters and pilot displays. The Hawk/32 processor also has a data recording system, used for the OES maintenance diagnostics system.

Technical Overview

The F-15 HIDEC SRFCS program has developed, implemented, and flight-tested a SRFCS. This program includes control reconfiguration, a head-up display (HUD) positive pilot alert system, and knowledge-based maintenance diagnostics.

The SRFCS program approach exploits the inherent control redundancies of advanced aircraft by fully utilizing its multiple control effectors and their secondary aerodynamic characteristics. This is accomplished by reconfiguration, after control effector failures, to allow control substitution by the remaining effectors. Instead of using massive redundant hardware on each effector to achieve fault tolerance and reliability, the redundant elements become the aerodynamic forces and moments produced by the other control effectors. The necessary forces and moments are generated by the alternate control surfaces to provide the required aircraft motion.

In today's fighter and transport–commercial aircraft, the control systems have the power and surface displacement to maneuver the aircraft in a very large flight envelope, with surplus force capacity available from each control surface. In the event of failure or loss of a control surface, the SRFCS utilizes this capability to reconfigure control commands to the remaining control surfaces, and thus preserve the maneuvering response.

Reconfiguration is one of the few technologies that holds promise to meet the availability and survivability requirements for aircraft in a hostile environment, while minimizing the complexity and costs of the system. Knowledge-based diagnostics address the timely and accurate fault isolation for maintenance and the unnecessary removal of non-failed equipment.

The technologies demonstrated in this flight program include control reconfiguration, fault detection and isolation, positive pilot alert, and maintenance diagnostics.

Control Mixer Reconfiguration Strategy

The core element of the reconfiguration strategy is the control mixer. The mixer can accept the outputs of a pre-existing set of control laws designed for an unimpaired airplane and reallocate these output commands for an impaired airplane to the surviving effectors.

Fault Detection and Isolation

Fault isolation is accomplished by hypothesis testing through sequential probability ratio tests, a scheme successfully used on the NASA F-8 digital fly-by-wire (DFBW) analytic redundancy management experiment.

Positive Pilot Alert

An integral part of the reconfiguration philosophy is the presentation of surviving flight control system status information to the pilot, including a situation assessment of the existing performance limits of the aircraft failure–damage.

Maintenance Diagnostics

The onboard computer-based fault diagnostic system for the flight control system reduces the RTOK (retest OK) and the CND (cannot duplicate) problems. This approach uses artificial intelligence (AI) to isolate failures occurring in flight. It uses available built-in test signals and additional sensor information on maneuver conditions and cockpit switch events that are present at the time of failure. Fact relationships are grouped in rules to find the most likely failure using an expert system forward-chaining inferencing process. Details of the inferencing process can be found in Ref. 6.

Self-Repairing Flight Control System and Technologies

The SRFCS tested was capable of emulating an impairment and reconfiguration after detection of the impairment. The SRFCS impairment–failure modes could be selected by the pilot and flown to assess the performance of the F-15 aircraft with and without the impairment. Figure 5 is a block diagram of the F-15 SRFCS implementation which includes both the standard mechanical and electronic control augmentation system (CAS). The F-15 HIDEC CAS serves to provide stability augmentation and command response enhancement through control laws implemented in a dual-channel DFCC.

The baseline mode is unchanged until an impairment is introduced. Two SRFCS commands, shown in Fig. 5, were added to the F-15 HIDEC CAS servo controller commands. The first command forces the control system to represent failure conditions. (This software module is for flight test only.) The second command adds a reconfiguration correction to each control surface servo controller.

The flight test aircraft is configured with three impairments that are selectable from the pilot's commands. All impairments affect the right-horizontal stabilator. The impairments are activated with software commands to the stabilator servo actuator to accurately represent the desired failure (Fig. 5). The commands negate the mechanical system inputs and pattern the stabilator for the desired impairment. Once the failure type is selected and activated by the pilot, it remains active throughout the fault detection sequence and

3

pilot evaluation of the reconfigured airplane. Both the failure and the correction commands disappear upon pilot deactivation of the reconfiguration test mode through a switch on the control stick.

Three types of failure modes were mechanized and flight-tested.

1. Locked at trim–representing hydraulic or mechanical failure.

2. Locked at an offset position–representing a failure caused by a hydraulic or mechanical jam. Values up to 6°-offset locked position can be flown.

3. Partial surface loss–representing a portion of the right stabilator missing–because of midair collision or battle damage of 50 percent, 80 percent, and 100 percent.

Fault Detection, Classification, and Estimation

The fault detection process involves pairwise hypothesis testing performed with sequential probability ratio tests to identify the failed flight control surfaces. Figure 6 shows a block diagram of the system impairment detection and classification (SIDC).

To show the difference in normal aircraft, as opposed to impaired aircraft response, acceleration residual errors are used to trigger the fault detection. After further processing, the acceleration residual errors identify the surface. This information is then sent to either the mixer, if local failures are identified, or the effector gain estimator (EGE) subroutine for partial surface loss failures.

The amount of surface damage is estimated as a span loss by the EGE, shown in Fig. 7. The missing span value is estimated using a Kalman filter estimator process by comparing aircraft acceleration data with a model of the damaged aircraft.

Reconfiguration

The fault detection isolation and estimation (FDIE) provides information on aircraft damage used in the reconfiguration mixer shown in Fig. 8. After failure detection and surface impairment damage estimation, the SRFCS system utilizes two aircraft models responding in real time to the same commands controlling the F-15 aircraft. These models continually output accelerations of both the undamaged and damaged aircraft.

Correction commands can be found that will cause the acceleration error to be reduced in the model. These same commands can also be added to the real aircraft surface commands to restore normal control. The calculation of these correction commands uses an inverse matrix multiplication described further in Ref. 6. The matrix is weighted with the control limits of the remaining control surfaces. This allows the forces and moments on the aircraft to be as close as possible to the forces and moments on the unimpaired aircraft.

Cockpit Display and Control

Controls in the cockpit allow the aircraft test pilot to select the type of impairment and the test mode desired. Either separate selection of the FDIE or reconfiguration mixer subroutines can be made, or the complete sequence of detection, isolation, and reconfiguration process can be activated. A reset or decouple command returns the aircraft to normal flight control operation.

After detection of the fault, a special pilot positive alert display is added to the HUD, showing the failed surface and the maneuver limits imposed by the reconfigured system. As shown in Fig. 9, this display cues the pilot not to exceed remaining flight control system limitations necessary for successful reconfigured flight. This is achieved if the pilot maintains a steering symbol inside a maneuver authority box. The box size is a function of the impairment and the current flight condition.

Onboard Expert System Maintenance Diagnostics

In addition to the reconfiguration, the SRFCS has an expert system capability that can detect and isolate system component failures occurring in routine aircraft use. These onboard diagnostics are adept at finding intermittent faults that happen only in flight and relate to casual events such as maneuver action, cooling temperature, pilot input sequence, or other fact relationships that may be impossible to reconstruct in postflight maintenance troubleshooting.

Flight Test Process

Figure 10 shows the flight envelope used for SRFCS development. The system was developed for the design envelope but it was also tested in the pilot maneuver envelope. The pilot could select various impairments and SRFCS test modes. Table 1 displays the test conditions flown: (a) impairments of the right stabilator; (b) the maneuver sequence, and (c) the SRFCS subroutine or test mode that could be selected by the pilot.

Tests were also conducted on the OES diagnostics using maneuver sequences designed to trigger the fault scenarios shown in Fig. 11. The SRFCS flights from December 1989 to March 1990 tested scenario 1 to scenario 5; scenario 6 had been flown successfully in March 1989.[1]

Preliminary Flight Test Results

The summary results of the FDIE are shown in Fig. 12. These results are preliminary; the test data are being analyzed for comparison of design response against flight response. The FDIE performance was directly related to the onboard simulation model fidelity.

The flight performance of the reconfiguration mixer was judged satisfactory by the NASA evaluation pilots, with the largest effects occurring for the 6°-locked stabilator impairments. This impairment requires large stick offsets just to maintain level flight while the reconfigured system permits the pilot to control with normal stick position. Figure 13 is an example of the stick position change. The indication is

4

that after reconfiguration, no offset is required to maneuver command of the reconfigured aircraft.

The OES diagnostics performed well, accurately determining the fault for all scenarios flown.

Conclusion

Flight tests were conducted with the self-repairing flight control system (SRFCS) installed on the NASA F-15 highly integrated digital electronic control (HIDEC) aircraft. The test results demonstrated the successful application of the SRFCS to a fighter aircraft. The value of flight testing was also well-documented with in-flight evaluation of all technical areas.

Key highlights of the flight results include:

1. The fault detection isolation and estimation (FDIE) overall performance was good, with no false detection for the maneuvers flown. The method used is dependent on aircraft model fidelity used in the system.

2. The reconfiguration technique clearly benefits the pilot for large impairments. The results indicate that the larger the impairments, the greater the benefit of a SRFCS.

3. The reconfiguration sequence of FDIE and subsequent reconfigured control is accurate for the selected maneuvers of the flight test program. The flight test showed that the accuracy of the detection system is related to the magnitude of impairment of the degraded control and the related size of the error signature.

4. The onboard expert system (OES) accurately identifies component faults of the kind that are intermittent with maneuver conditions.

References

[1] Grumman Aircraft Systems, *Control Reconfigurable Combat Aircraft, Architecture and Simulation Development*, Final Report, AFWAL-TR-88-3118.

[2] Anderson, J., C. Clark, P. Madsen, and F. Unfriend, *USAF AFTI/F-16 Self-Repairing Flight Control System (SRFCS) Simulation*, NAECON, Dayton, Ohio, 1987.

[3] Charles River Analytics Inc., *Failure Detection, Isolation, and Estimation for Aircraft Flight Control Systems Subjected to Actuator Failure and Surface Damage*, Final Report, WRDC-TR-89-3058, May 1989.

[4] Lear Astronics Corporation, *Reconfiguration Strategies for Aircraft with Flight Control Systems Subjected to Actuator Failure/Damage*, Final Report, WRDC-TR-893052, May 1989.

[5] Weinstein, W., W. Posingies, R. Eslinger, and H. Gross, "Control Reconfigurable Combat Aircraft Flight Control System Development," AIAA Guidance, Navigation and Control Conference, Williamsburg, Virginia, 1986.

[6] Urnes, James M., James F. Stewert, and Robert Eslinger, "Flight Demonstration of a Self Repairing Flight Control System in a NASA F-15 Fighter Aircraft," AGARD Guidance and Control Panel 49th Symposium, Toulouse, France, October 1986.

Table 1. Test conditions.

(a) Right-Stabilator Impairment.
Locked at trim
Locked at +2°
Locked at +4°
Locked at +6°
80-percent missing span
100-percent missing span
50-percent missing span

(b) Test Maneuvers.
Pitch and roll stick doublets
Pushover and pullup
3-g windup turn
3-g bank-to-bank roll

(c) Configuration.
No impairment
Impairment
Impairment with fault detection
Impairment with effector estimator
Impairment with reconfiguration mixer
Impairment with complete reconfiguration sequence
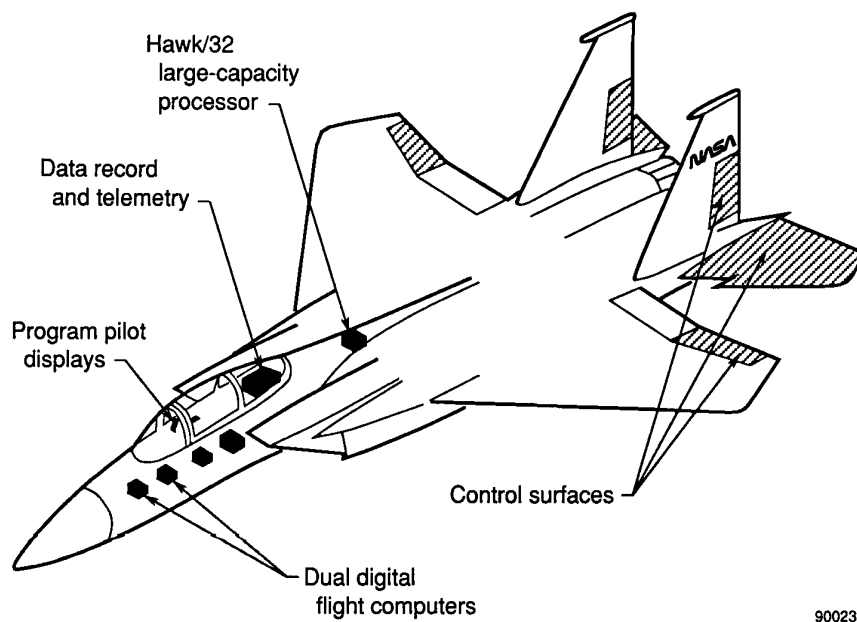
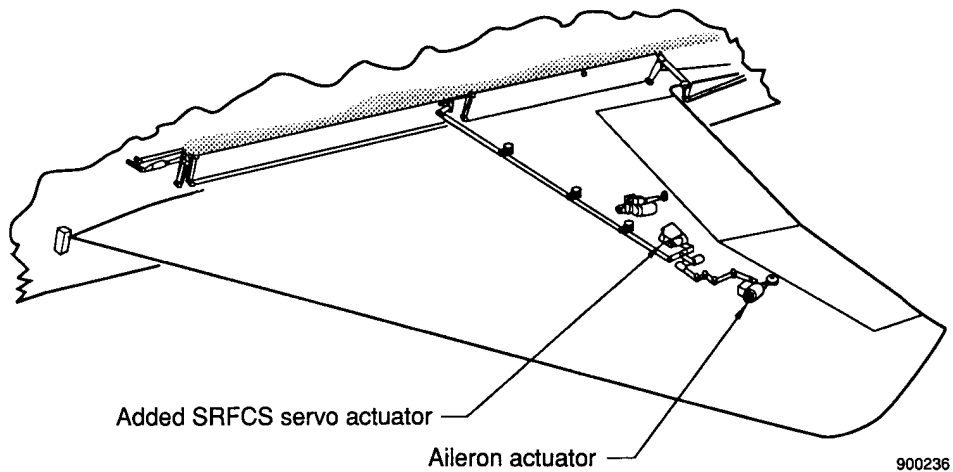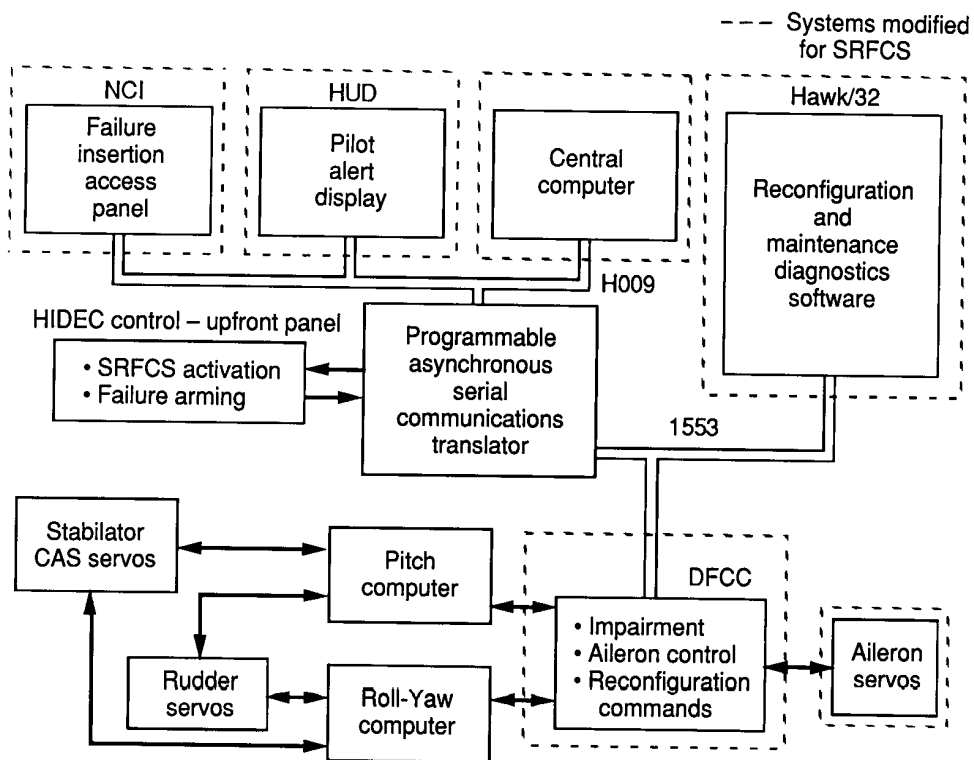Fig. 1 NASA F-15 test vehicle offers high-capacity software for self-repairing flight demonstration.

Added SRFCS servo actuator

Aileron actuator

900236

Fig. 2 Modified aileron control mechanism.

	Memory, bytes	Computation time, msec
Hawk/32 processor		
Program executive control	29,600	—
Maintenance diagnostics	38,395	3.2
Mixer	10,179	2.6
SYSDYN aircraft models	49,770	3.9
EGE	14,222	8.8
FDIE	30,357	19.3
Data handling (flight test)	6,681	1.3
Access/control (flight test)	128,548	—
Displays	13,675	0.6
Digital flight computer		
CAS control laws with reconfiguration	Pitch 13,640 Roll 13,900	Pitch 3.18 Roll 4.19

900237

Fig. 3 F-15 aircraft software requirements.

7

NCI

Failure
insertion
access
panel

HUD

Pilot
alert
display

Central
computer

Hawk/32

Reconfiguration
and
maintenance
diagnostics
software

H009

HIDEC control – upfront panel

• SRFCS activation
• Failure arming

Programmable
asynchronous
serial
communications
translator

1553

Stabilator
CAS servos

Pitch
computer

DFCC

• Impairment
• Aileron control
• Reconfiguration
commands

Aileron
servos

Rudder
servos

Roll-Yaw
computer

900238

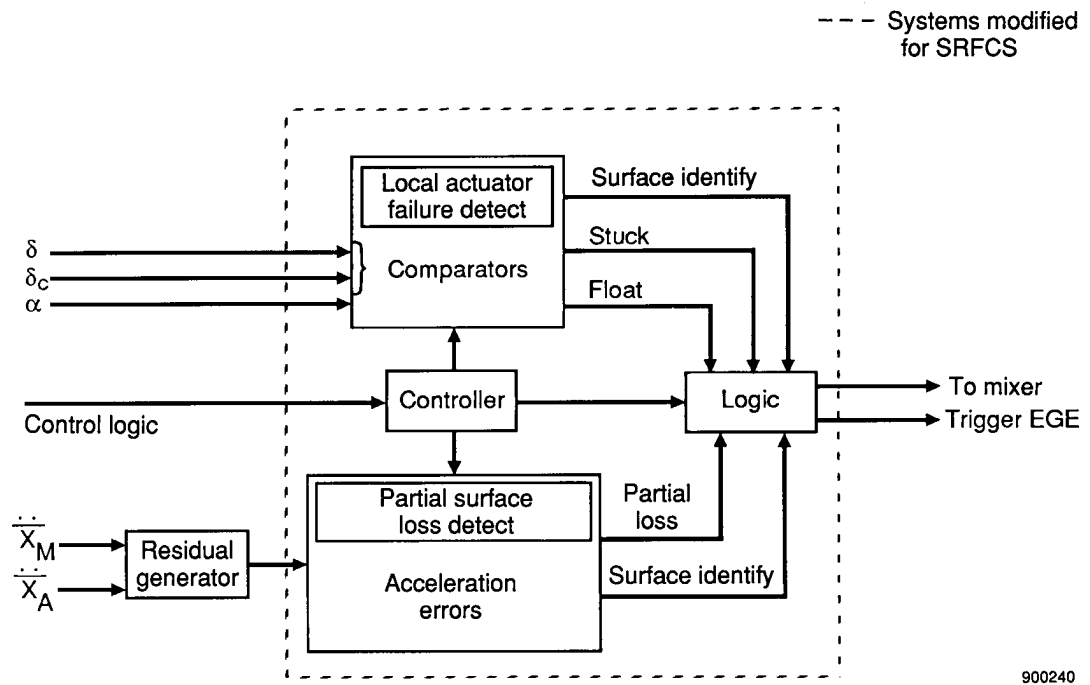Fig. 4 F-15 aircraft SRFCS implementation.
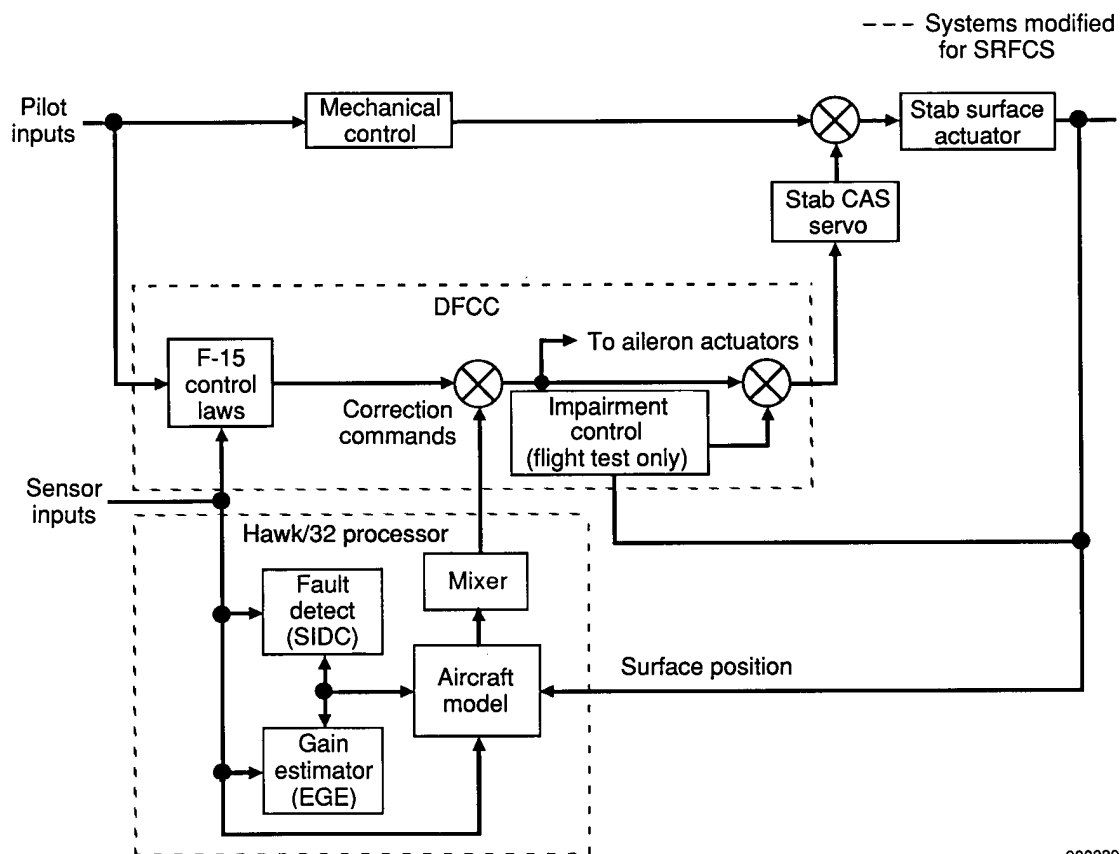
Fig. 5 SRFCS implementation.

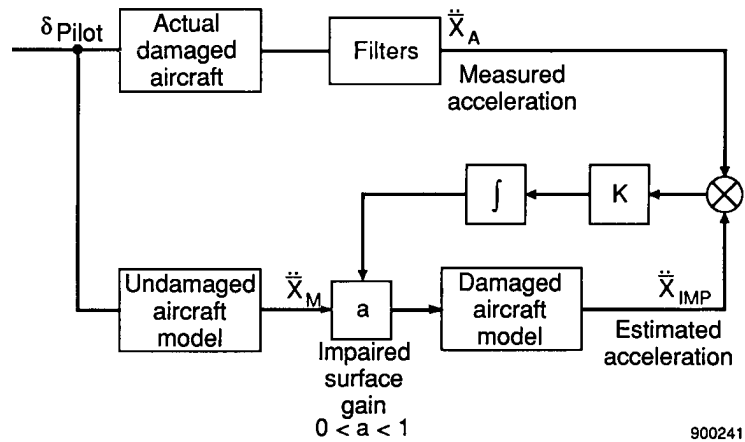Fig. 6 System impairment detection and classification of control surface failures.

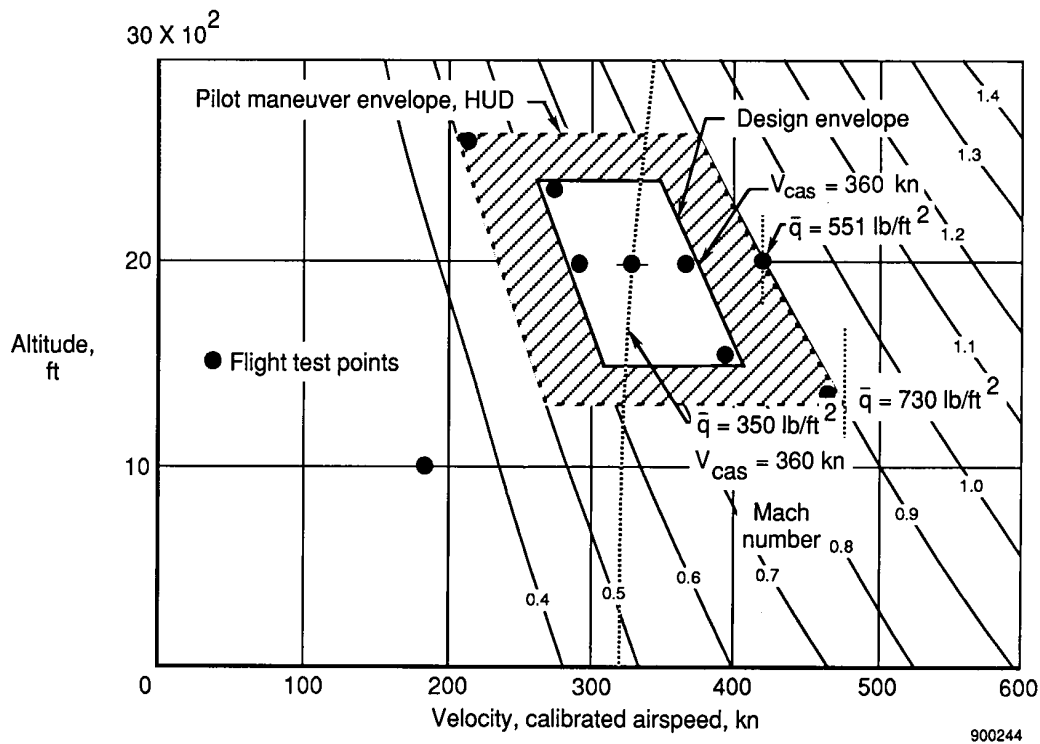Fig. 7 EGE process obtains impaired surface capability.

10

δ_{Pilot} — CAS control laws — δ_{CAS} — $\delta_{Surface}$

$\Delta\bar{\delta}$

Sensors

Surface positions

SYSDYN models:

Unimpaired

Impaired

$\ddot{\bar{X}}_M$ $\ddot{\bar{X}}_{Error}$ $W\left[B^*W\right]^{-1}$ $\Delta\bar{\delta_i}$

$\ddot{\bar{X}}_{IMP}$

W

Impairments and limits

Z^{-1}

900242

Fig. 8 Reconfiguration mixer restores control.

250
300
350
400

40
30
20
10
0

10 — 10

17   18   19

20500

5 — 5

9
6
3
0

20000

19500

3

Added display, maneuver limits

Pilot action

RESET CAS

R STAB

Failed surface

5 - - - - 5

Added display, rudder limits

10 - - - - 10

900243

Fig. 9 Pilot positive alert display triggered when fault is identified.

11

Fig. 10 F-15 SRFCS flight demonstration test envelope.

Fault scenario	Maneuver conditions	Failure indication major system	Subsystem failed	Cause
1	>3g	Roll CAS disengage	Dynamic pressure sensor	Connector fails under g load
2	1-g small pitch inputs	None	Stabilator surface	Actuator connecting pin
3	1-g small pitch inputs	Pitch, roll CAS disengage	Stabilator actuator	Hydraulic
4	2-g turn	Autopilot disengage	Inertial navigation system	Platform stabilization fails under g load
5	5-g turn	Pitch, roll CAS disengage	Pitch computer	Card A loose connection under g load
6	Pull-up	CAS disengage	Right angle-of-attack sensor	Excessive friction in rotor

Fig. 11 In-flight maintenance diagnostics scenarios.

Fault detection, right stabilator partial missing

Correction detection and verification: 60 percent
Detection, no verification: 40 percent
False detection or verification: 0 percent

Fault detection, right stabilitor locked

Correct detection: 100 percent

Estimate of remaining stabilator surface

Correct value, span missing: 51 percent
(±20 percent tolerance)

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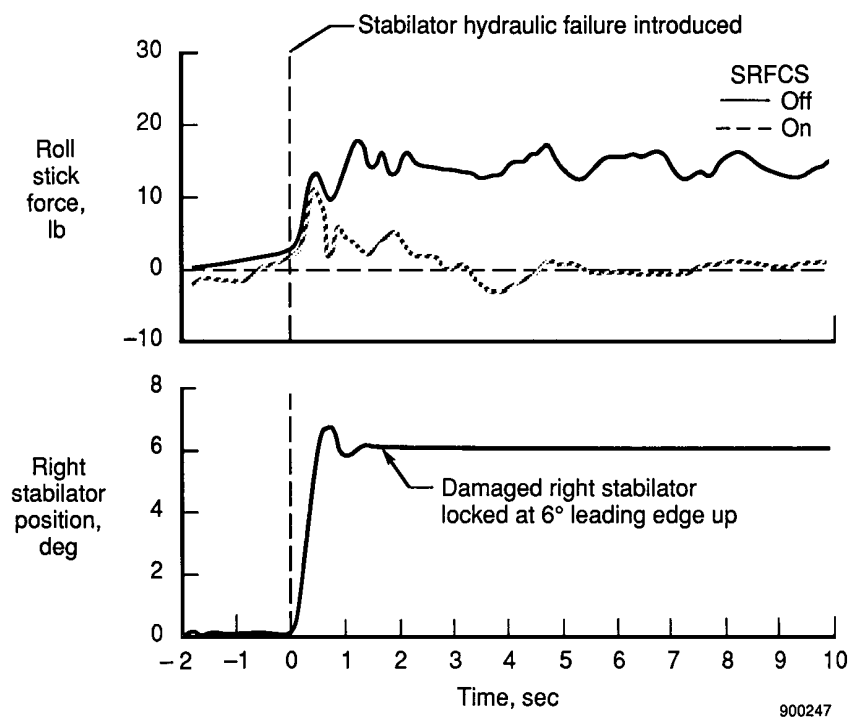
Fig. 12 Summary results of FDIE.

Fig. 13 F-15 SRFCS flight data; Mach 0.7, altitude = 20,000 ft.

13

Report Documentation Page

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